

Analysis of Transient HC, CO, NO_x and CO₂ Emissions from a GDI Engine using Fast Response Gas Analyzers

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ABSTRACT

A study has been conducted to measure the transient HC, NO_x, CO, CO₂ and particulate emissions from a modern 1.6-liter, Euro IV-stage turbocharged Gasoline Direct Injection (GDI) passenger car engine. The tests were conducted using ultra-fast-response analyzers with millisecond response times so that the real-time effects of the individual combustion events and the ECU's start strategy could be studied.

The results show that through the use of an aggressive cold start calibration strategy, the catalyst is very efficient after light-off at about 30s. However, during this same period, there are signs of partial misfires and rich AFR excursions, both of which contribute to the overall tailpipe emissions. The data from the fast-response analyzers allowed clear discrimination between rich events and partial misfires and would allow appropriate calibration actions to be taken.

NO_x conversion was seen to be highly transient, with very big changes in tailpipe NO_x emissions occurring corresponding to the fuelling control system AFR switching frequency. Under lean AFR bias conditions, particularly after a lean AFR disturbance, significant NO_x breakthrough was seen. ECU optimization using fast-response analyzers could further improve this vehicle's emissions calibration.

INTRODUCTION

The proportion of gasoline vehicles operating with Gasoline Direct Injection (GDI) fuelling systems is steadily increasing due to the benefits in specific power output, fuel efficiency and fuelling control.

One reason for the significant benefits of GDI is the charge cooling effect of the injected fuel resulting in improved knock resistance, allowing use of increased compression ratios which in turn lead to improvements in efficiency and specific power output.

GDI technology also improves fuelling control, notably allowing lean stratified operation, with further benefits in fuel economy through reduced throttling losses. Initially, GDI engines were principally developed to exploit the fuel economy advantages of lean stratified operation within suitable operating envelopes. However, the emissions control difficulties associated with lean operation have produced a trend for stoichiometric homogeneous GDI engines. These have been emerging into the fleet for several years now and are gradually replacing the older Port-Fuel-Injected (PFI) gasoline technology.

Whilst GDI offers many advantages over PFI, there can be issues relating to fuel preparation, even with the intake-stroke injection strategies typically used in the case of homogeneous GDI. These fuel preparation issues are due to the fuel spray impinging on the surfaces of the combustion chamber and due to the reduced time for fuel vaporization compared with previous PFI technology where injecting on to the back of the intake valve produced good fuel vaporization.

Further improvements in fuel economy are possible through turbocharging the GDI engine, allowing still higher specific power outputs with further opportunities for engine downsizing (hence reduced friction and throttling losses at part load). However, in the case of turbocharged GDI engines, the presence of a turbocharger upstream of the catalyst tends to delay catalyst light-off and therefore more aggressive catalyst heating strategies are required.

Fortunately the enhanced fuelling control available with GDI technology assists with these aggressive catalyst light-off strategies through the capability of running multiple injections in a single cycle. This allows a degree of mixture stratification where a small early injection can provide a lean homogeneous mixture which is supplemented by a late injection immediately before ignition to give a richer mixture around the spark plug. This improves combustion stability allowing very late spark timings to be used with very high heat output and low emissions.

One of the benefits of GDI technology is that the fuel is delivered directly into the cylinders rather than into the intake port (as is the case in port-fuel-injected engines). This removes many of the fuel hold-up (fuel puddling) issues of PFI engines and allows the use of simpler transient fuel control algorithms. During the cold start, the fuel puddling issues in PFI engines were particularly significant due to the lower level of fuel vaporization on the colder engine surfaces; this lead to significant uncertainty in fuel delivery quantity and vapor content to the cylinder, particularly taking into account variations in fuel volatility. With GDI, fuel quantities can be controlled on a cycle-by-cycle basis allowing more precise optimization of cold start emissions.

In order to take advantage of the improved control available with GDI engines, the engine calibration engineer needs to be able to identify emissions issues and the effect of calibration changes with a very high time resolution. For this reason, fast-response emissions instrumentation is often used to optimize the cold start emissions of GDI engines. The most common analyzer used is a Fast-response Flame Ionization Detector (FID) which can measure cycle-by-cycle engine-out HC emissions. Fast-response CO, CO₂ and NO_x are also used to help optimize the system.

Particle emissions from GDI engines are also a concern. Significantly higher numbers of particles have been measured from GDI engines compared with PFI [1,2].

This paper concentrates on gaseous emissions results from a latest-generation GDI vehicle and contrasts these measurements with impending and anticipated European legislation. Emissions from the vehicle are measured using conventional techniques and fast-response analyzers.

APPARATUS

The main items used for these experiments were:

- Peugeot 308 1.6 THP vehicle (150ps)
- Froude-Hofmann chassis dynamometer + robot driver
- Cambustion NDIR500 2-channel fast-response CO & CO₂ analyzer
- Cambustion CLD500 2-channel fast-response NO_x analyzer

- Cambustion HFR500 2 channel fast-response HC analyzer
- Horiba MEXA 7400DEGR emissions bench

VEHICLE AND ENGINE

This vehicle was chosen for study because it represents current production GDI technology. Broadly speaking, vehicles of similar technological complexity and performance are produced by other European and Japanese manufacturers. Similar technology (but larger displacement) is evident within North America and emerging economies are currently investigating production of such engines for their future product development.

The engine fitted to the vehicle is a joint development between BMW and Peugeot and is known as the Prince engine. The information available for this engine is limited to that available in the public domain [3,4].

- The maximum output = 105 kW @ 5500 rpm; max torque = 240 Nm @ 1400 rpm - 4000 rpm.
- It runs a stoichiometric fuel injection strategy with a twin-scroll turbocharger running at a max boost of 0.8 bar.
- The cylinder capacity is 1596 cm³ with a bore of 77mm and a stroke of 85.8mm; the compression ratio is 10.5:1.
- It also has infinitely variable inlet cam phasing. The vehicles powered by this engine meet EU4 and ULEV2 regulations.

No details of the injector hardware are available but, from observation, it is clear that the injector is fitted in the side of the cylinder head and the axis of the injector is almost perpendicular to the piston axis.

The emissions system on this vehicle consisted of a close-coupled catalyst with two substrates, the first of which has a high cell density to aid rapid light-off. The production catalyst was hydrothermally aged for 15 hours at 950°C to simulate approximately 50,000 miles of vehicle operation.

Thermocouples were inserted into the catalyst substrates at 1" (25mm) measured axially from the front face of each substrate and at 1" (25mm) from the rear face of the second substrate.

INSTRUMENTATION

The main focus of this paper was the measurement of gaseous emissions. Sample points were fitted for engine-out and post-catalyst emissions. The engine-out location was immediately after the turbocharger (and therefore approximately 100mm upstream of the 3-way catalyst front face). The post-catalyst sampling point was positioned approximately 100mm

downstream from the rear face of the catalyst. The vehicle's OBD port was monitored for engine speed and spark timing.

FAST-RESPONSE ANALYZERS

These items are described along with various applications and technical references [5, 6, 7, 8 and 9] but briefly: the fast-response gas analyzers rely on the industry-standard measurement techniques of FID, CLD and NDIR for measurement of unburned hydrocarbons (HC), nitric oxide (NO), carbon monoxide & carbon dioxide (CO & CO₂) respectively. These analyzers are designed with specialized sampling systems yielding response times of just a few milliseconds and are therefore able to resolve the very fast transient emissions associated with cold start fuelling, individual misfires etc.

CONVENTIONAL EMISSIONS BENCH AND DILUTION TUNNEL

Horiba MEXA 7400DEGR measuring into a full-flow dilution tunnel. Emissions were measured in real-time through the cycle to allow a second-by-second emissions calculation to be carried out.

DYNAMOMETER FACILITIES

A Froude-Hofmann robot driver was employed to drive a New European Drive Cycle (NEDC) on a Froude-Hofmann chassis dynamometer.

DATA ACQUISITION

Two data acquisition systems were used: the data from the fast-response analyzers were logged at 1kHz; the lower frequency signals were logged at 10Hz.

EXPERIMENTAL

The vehicle was evaluated over several NEDCs with different test configurations. A robot driver was used for drive-cycle repeatability and rapid cooling was used between tests to increase experimental throughput. These techniques have proved previously to produce good repeatability and equivalence to an overnight soak with a human driver.

There were insufficient sample points available to record simultaneously all of the gas components within a single test. Therefore, several repeat tests were conducted with different analyzer sample locations.

RESULTS AND DISCUSSION

OVERALL TAILPIPE EMISSIONS

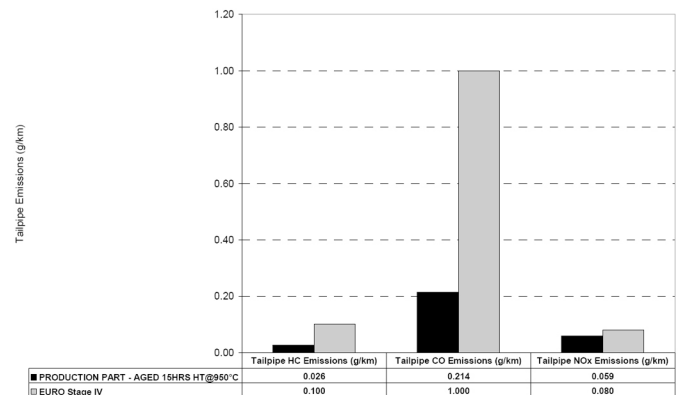


Figure 1. Overall Cycle Emissions of HC, CO & NOx vs EURO IV limits

Overall emissions of HC and CO are well within Stage 4 legislative targets, even at this level of catalyst ageing. This is quite impressive and suggests a high level of optimization of engine-out emissions has been applied in this case along with a highly effective catalyst.

Further analysis of the emissions results measured from the conventional emissions analyzers revealed that most of the tailpipe emissions were emitted during the cold start.

Note that the cycle is 11 km long so total mass emissions can be calculated by multiplying the cycle emissions in [Figure 1](#) by 11. This allows comparison with mass emissions shown in the following figures.

COLD START (0-100 SECONDS) EMISSIONS MEASURED WITH FAST-RESPONSE ANALYZERS

[Figure 2](#) shows HC measurements made during the cold start (first 100 seconds) of the NEDC using fast-response HC analyzers. Pre-and post-catalyst HC concentrations are shown along with cumulative mass emissions calculated from the concentrations and exhaust mass flow. Note that exhaust mass flow is a relatively slow signal in this case, which can lead to difficulties in attributing an exhaust mass flow to a pollutant concentration; these raw mass emissions should be considered to be indicative rather than absolute.